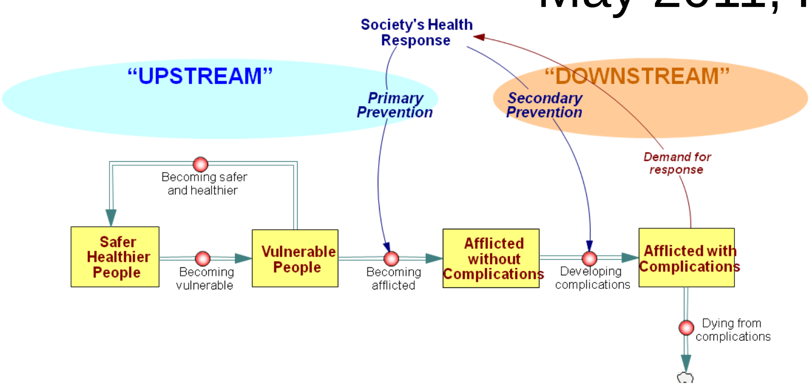
Institute for Systems Science & Health

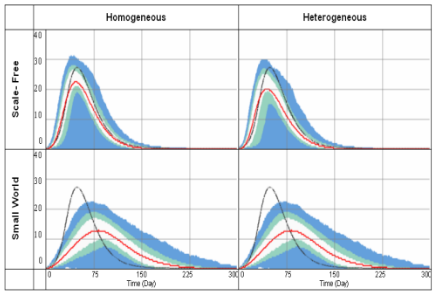
System Dynamics Track

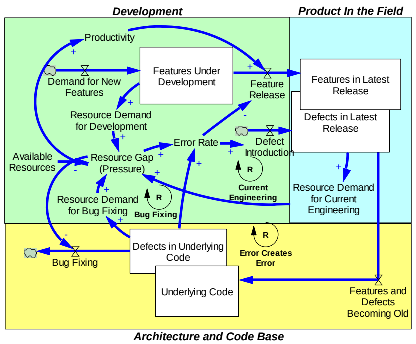
Stocks, flows, and system structure diagrams

Hazhir Rahmandad
Virginia Tech

May 2011, Pittsburgh, PA





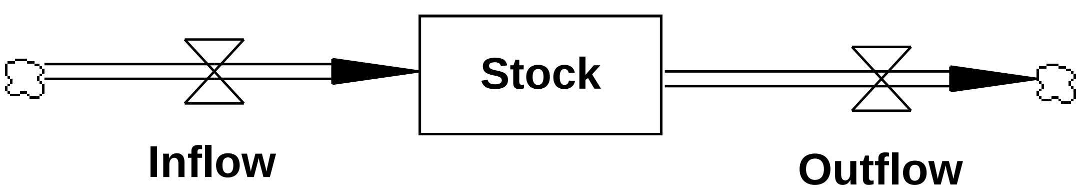


Process Overview

- Problem Articulation
- Mapping Dynamic Hypotheses
  - **Operational (causal) thinking**
  - **The feedback perspective**
  - **Stocks and flows**
- Model Formulation
- Model Testing
- Policy Design and Evaluation

Stocks describe state of systems

- Stocks (also “levels”, “state variables”, “compartments”) represent accumulations
  - These capture the “state of the system”, once known, we know all we can about possible future trajectories of the system.
- Stocks can be measured at one instant in time (snapshot or freeze test)
- Stocks *only* change by flows going into/out of them; no inputs can immediately change stocks
- Represented by rectangles in stock and flow diagrams



$$\text{stock}(t) = \int_{t_0}^{t} (\text{inflow} - \text{outflow})dt + \text{stock}(t_0) \quad \text{or} \quad \frac{d(\text{stock})}{dt} = \text{inflow} - \text{outflow}$$

Capturing Stocks

- Think operationally: what is physically influencing what?
  - Think like a physicist: what are the causal mechanisms?
- Find stocks: They move relatively slowly:
  - Start with snapshot test
  - Too slow and they don't change in time frames of interest in problem➔ a parameter, not a stock
  - Too fast and their dynamics are predicted by other stocks (no need to capture their internal dynamics)➔ an auxiliary variable
- Be consistent in units for stock and flow chains
- Stock and flow dynamics are non-intuitive, we use integration (analytical or numerical).

Stock Examples in SIRS

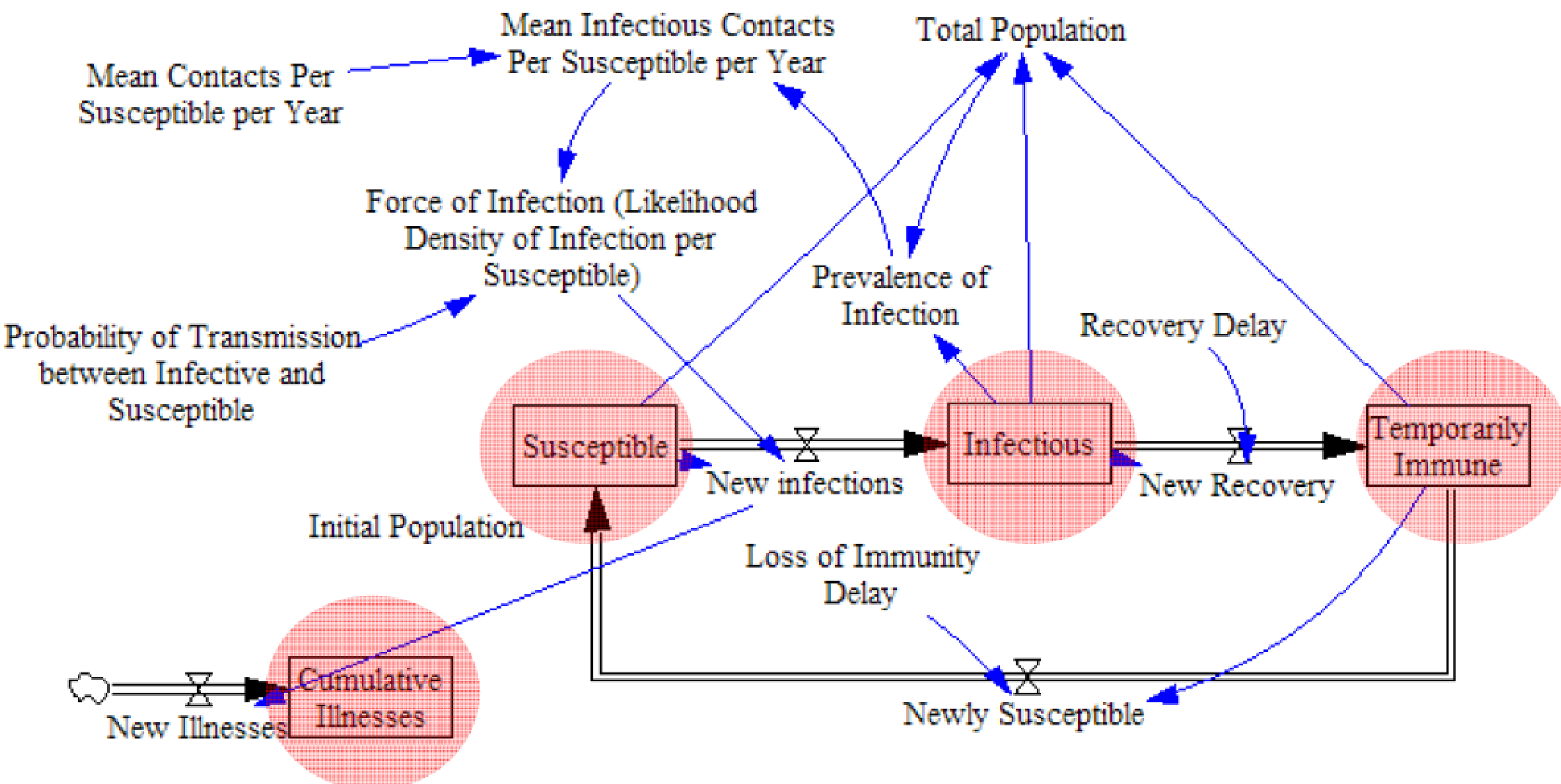


Figure Credit: Dr. Nate Osgood

Stocks are critical

- They determine the current state of the system:
  - Needed to form expectations about future
  - Provide the basis for making decisions
- Their build up and decay are the force behind the dynamics of systems
- The lead to inertia and delays
- They provide one way of understanding the complexity of a system

Flows show changes in system state

- Any change in stocks happens through flows (also “fluxes”, “rates”, “derivatives”)
  - Expressed per some time unit: stock of unit X (e.g. persons) will have flows measured in X/Time Unit (e.g. Persons/Month)
- Flows are measured over a period of time, by considering the average rate of accumulation over the period, and dividing by period’s length:
  - e.g. Incidence rate is calculated by accumulating people over a year, revenue is $/Month.
  - Can take limits to find a flow at a specific point

Flows in SIRS

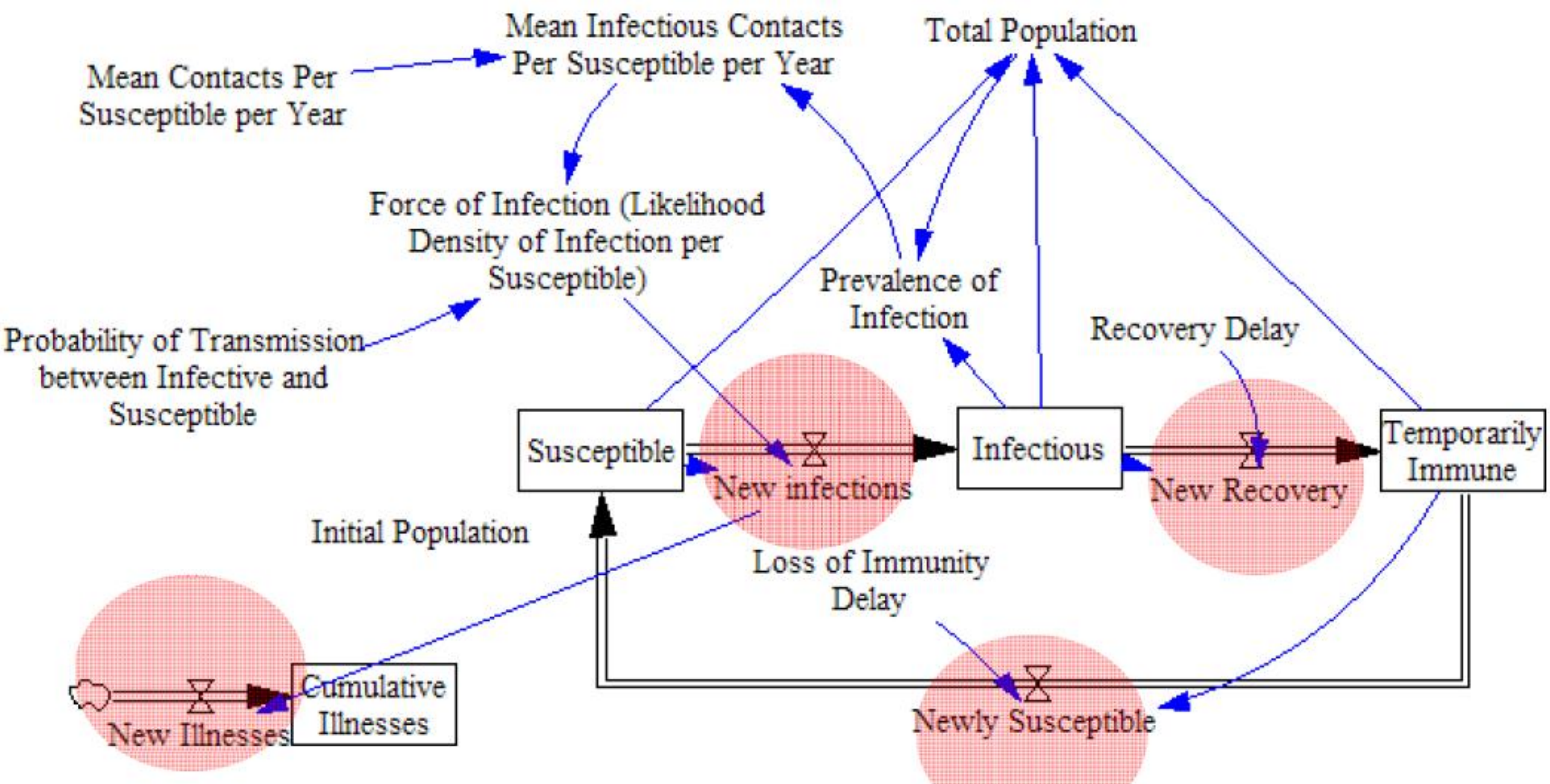


Figure Credit: Dr. Nate Osgood

Examples of stocks and flows

- Stocks:
  - People of different types (e.g. age x-y, susceptible, high risk, pregnant)
  - Beds in hospital
  - Money in bank account
  - Blood sugar
  - Stored energy
  - Vaccine stockpile
  - Water in bathtub
- Flows:
  - Incidents (e.g. people/month)
  - Rate of Recovery
  - Rate of Mortality
  - Rate of births
  - Revenue
  - Spending rate
  - Energy expenditure
  - Vaccine administration
  - Rate of shipping goods

Auxiliary Variables

- Concepts that can be calculated based on stocks/flows at the current time
  - They provide conceptual clarity and layout the mechanisms more clearly, but we can remove them without changing the mathematical structure of the model
  - They help with model transparency because they can be reused at many places
  - They provide easy points for modifying the structure of model
  - They are convenient for reporting and analyzing models

Auxiliary Variables in Example Model

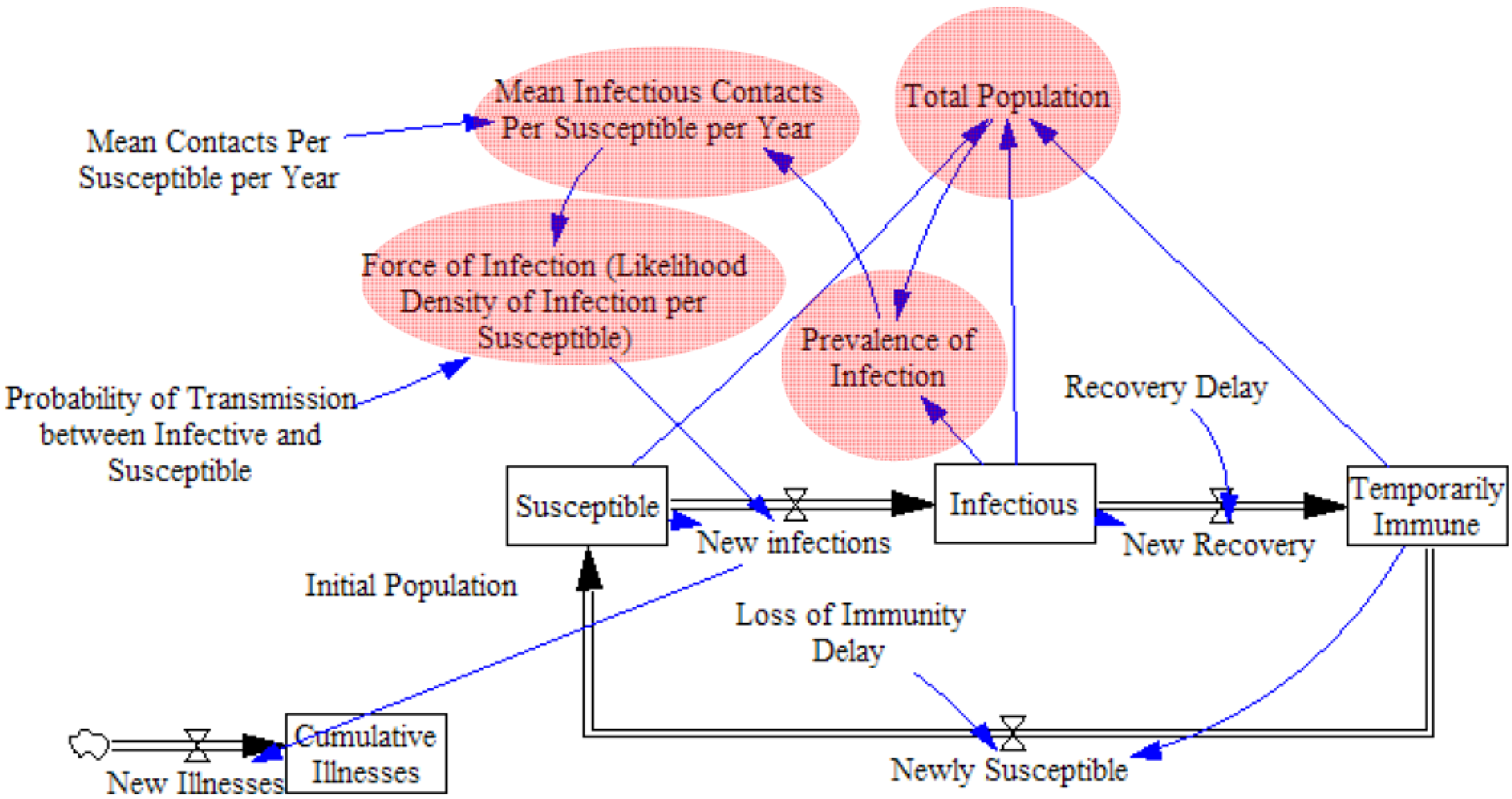


Figure Credit: Dr. Nate Osgood

Parameters and Time Series

- Numerical inputs to the model
  - Do not change endogenously in model calculations
  - May include constants and time series
  - They are used in different formulations to calculate auxiliaries, rates, and initial values of stocks
- They can be estimated through different channels:
  - Expert judgment
  - Literature
  - Mechanism based calculations
  - Calibration and estimation

Examples of Parameters in SIRS

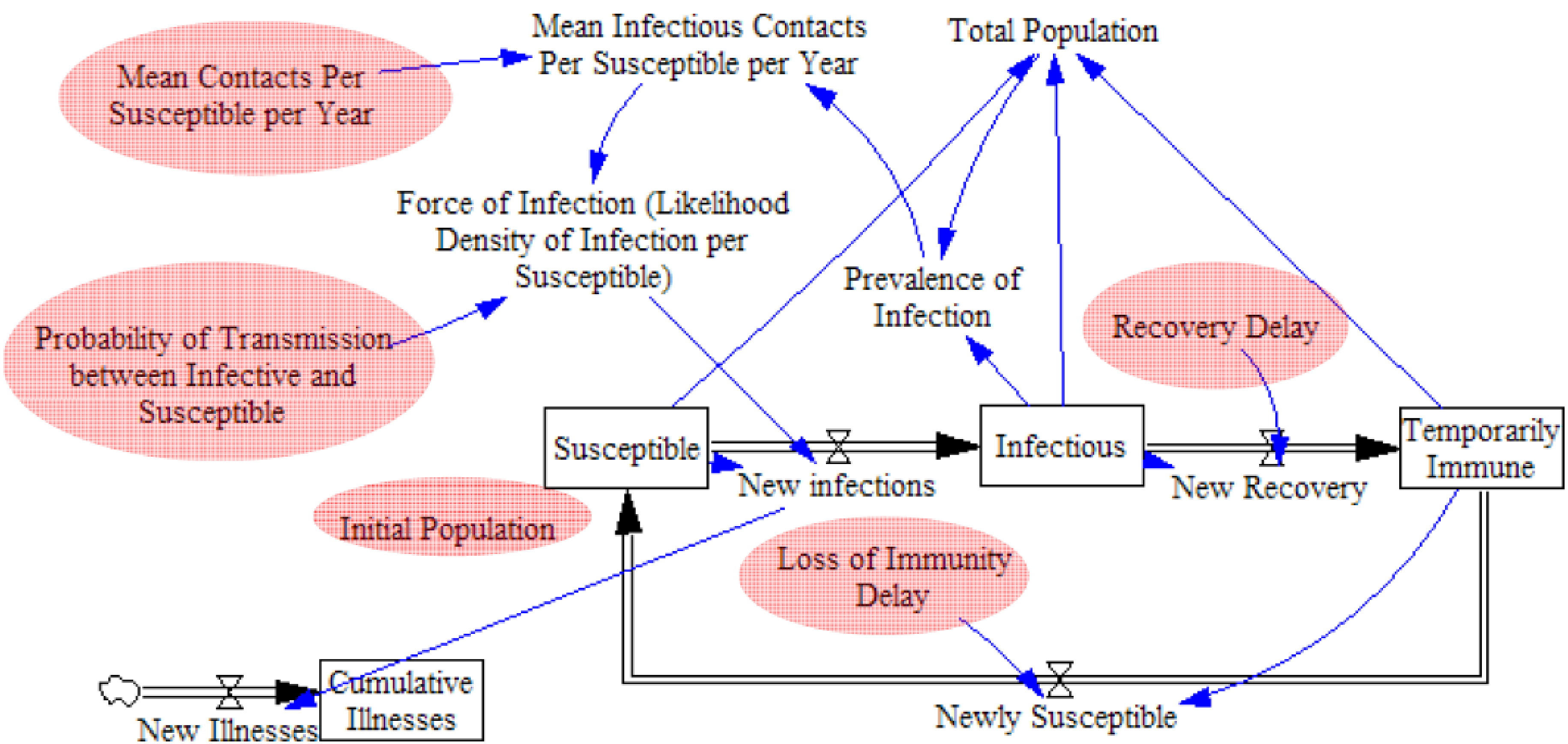


Figure Credit: Dr. Nate Osgood

Example Parameter Table

Table 1. Parameter values for the model

Parameter	Description	Value	Reference
β	Infection rate	10^{-7} person^{-1}·day^{-1}	See text
c	Names generated per index	50	1, 9
p	Fraction of infectees named by index	0.5	See text
N	Population size	10^7	See text
r_1	Disease stage 1 rate	(3 days)$^{-1}$	1
r_2	Disease stage 2 rate	(8 days)$^{-1}$	1
r_3	Disease stage 3 rate	(3 days)$^{-1}$	1
r_4	Disease stage 4 rate	(12 days)$^{-1}$	1
n	Number of vaccinators	5000	11
μ	Service rate	50/day (TV), 200/day (MV)	12
h	Fraction febrile in stage 3	0.9	See text
α	Quarantine rate	(5 days)$^{-1}$	4
v_0	Vaccine efficacy, stage 0	0.975	13, 14
v_1	Vaccine efficacy, stage 1	0.975	13, 14
δ	Smallpox death rate	0.3	1
f	Vaccination fatality rate	10^{-6}	1
$I_1^0(0)$	Initial number infected	10^3	See text

Source: Kaplan, E.H., D.L. Craft, L.M. Wein. 2002. Emergency response to a smallpox attack: The case for mass vaccination. *Proceedings of the National Academy of Sciences 99(16) 10935-10940.*

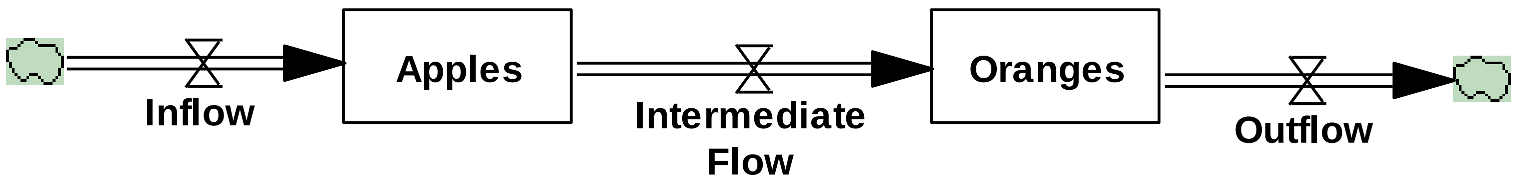
Hands On: Variable type

- Categorize these variables as stocks, flows, auxiliaries, or parameters:
- Hospital admissions, room temperature, salary, age, GPA, investment, heart attacks, arrests, position, price, prevalence rate, firm's revenue, government deficit, depreciation, # of doctors in ER, Exchange rate,

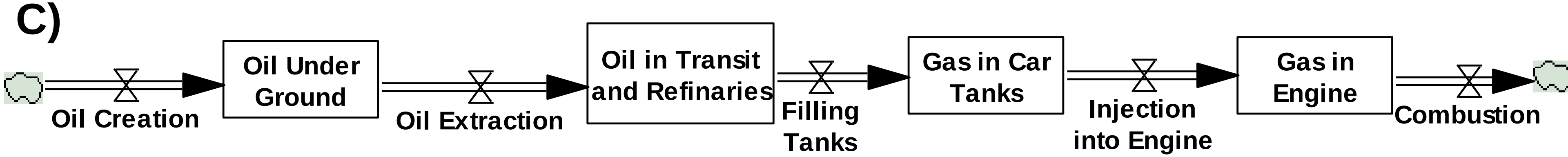
Hands On: Critique structures and suggest improvements

A)

B)

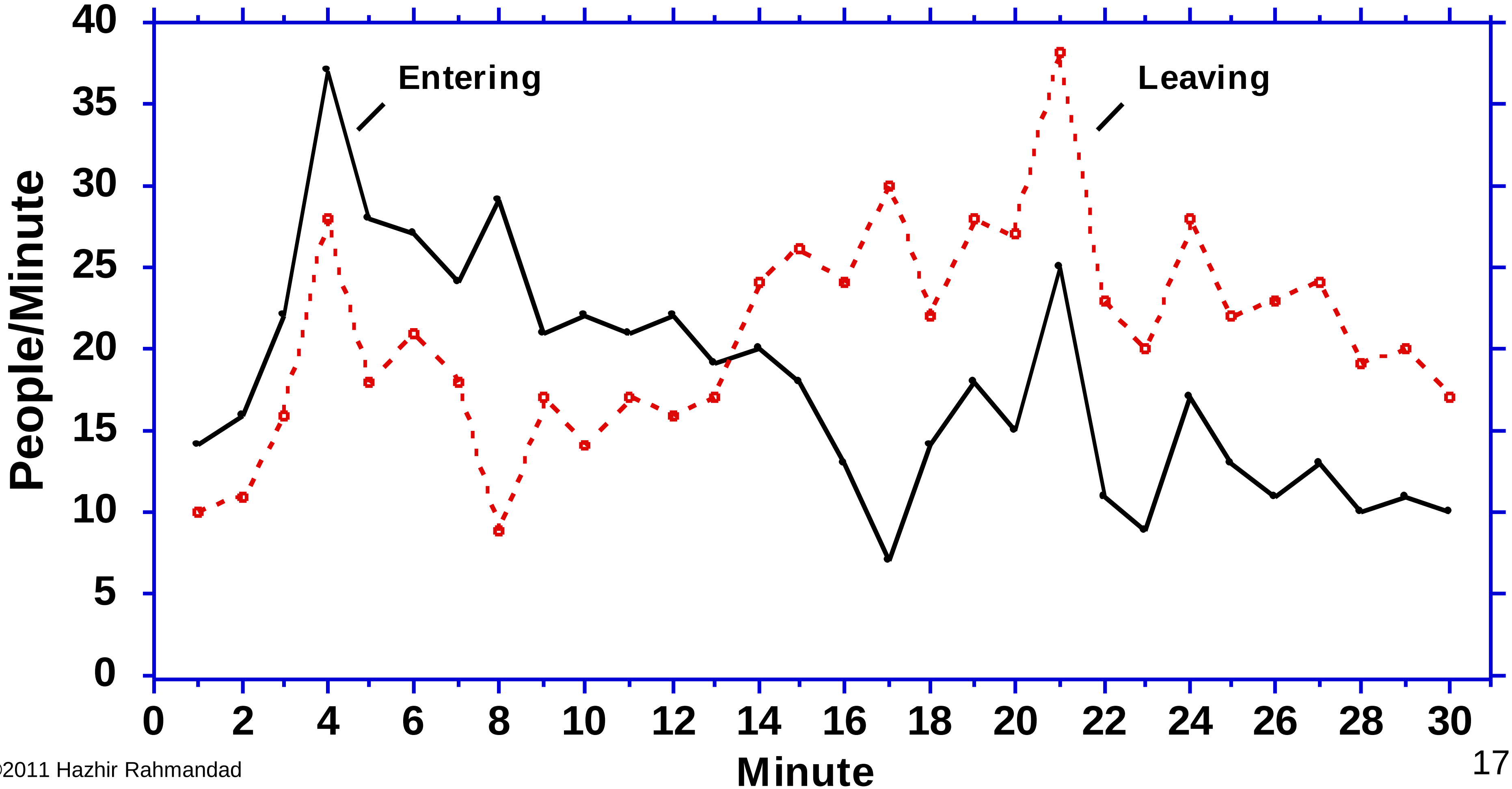


C)

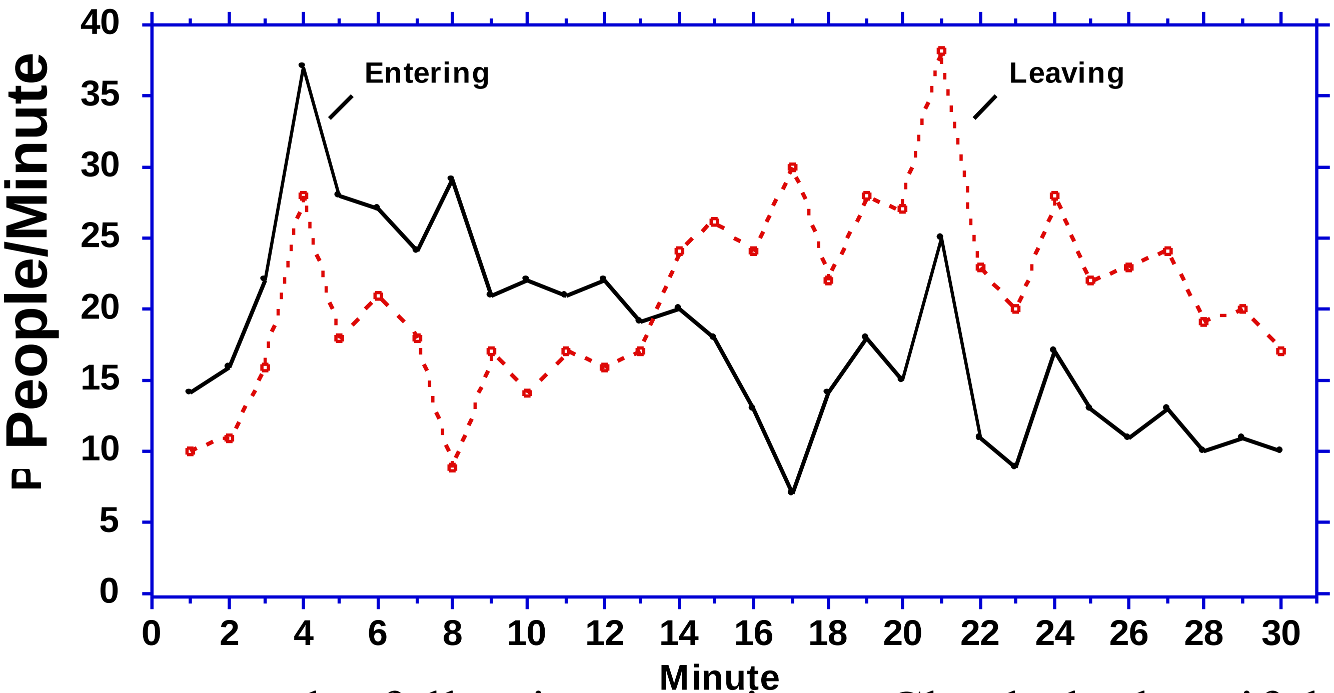


Dynamics of Stocks and Flows

The graph below shows the number of people entering and leaving a department store over a 30 minute period.



Answer these questions individually, write down your answers.



Please answer the following questions. Check the box if the answer cann
be determined from the information provided.

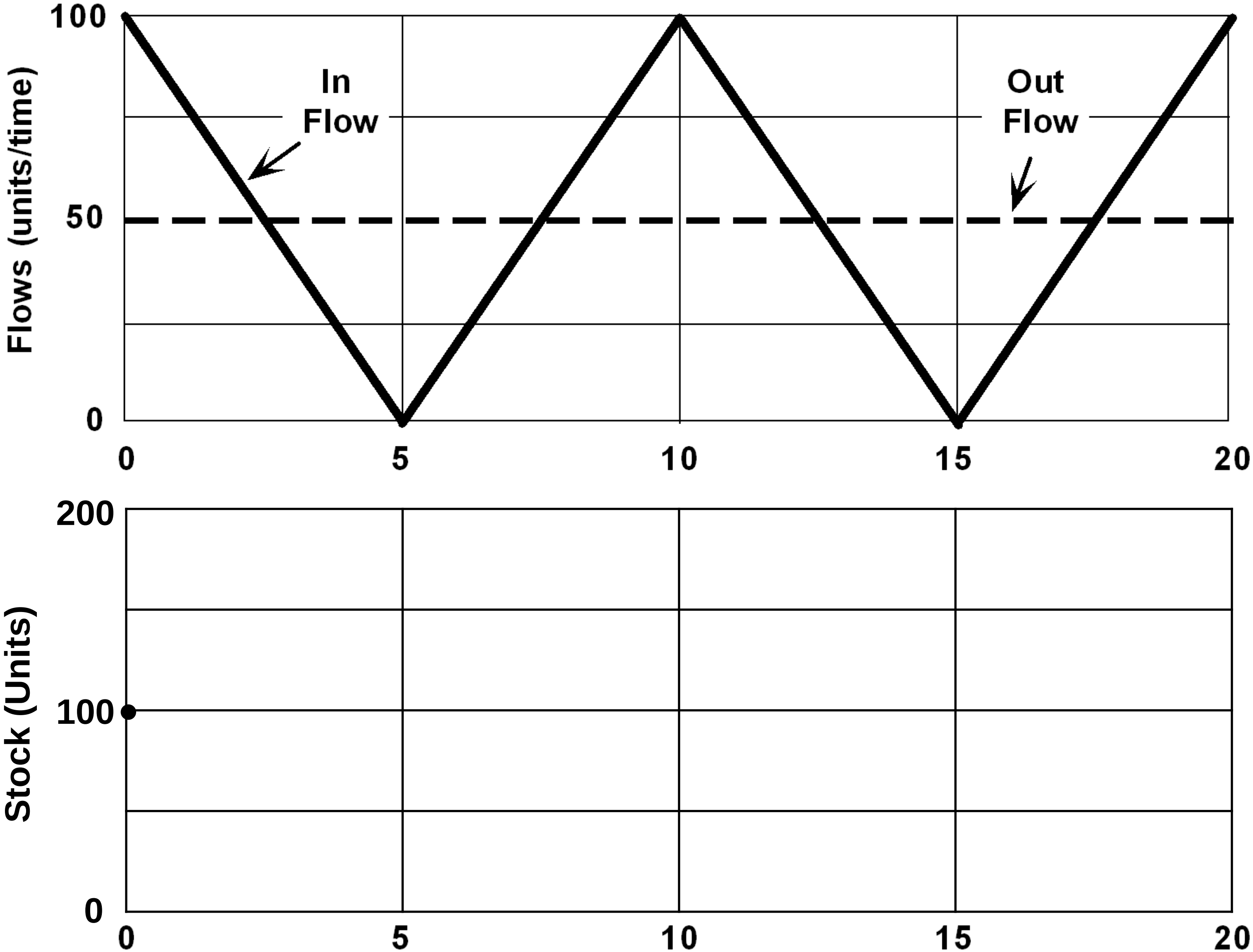
1. During which minute were the most people in the store?

Minute ________ ☐ Can’t be determined

2. During which minute were the fewest people in the store?

Minute ________ ☐ Can’t be determined

Hands On: Graphical Integration



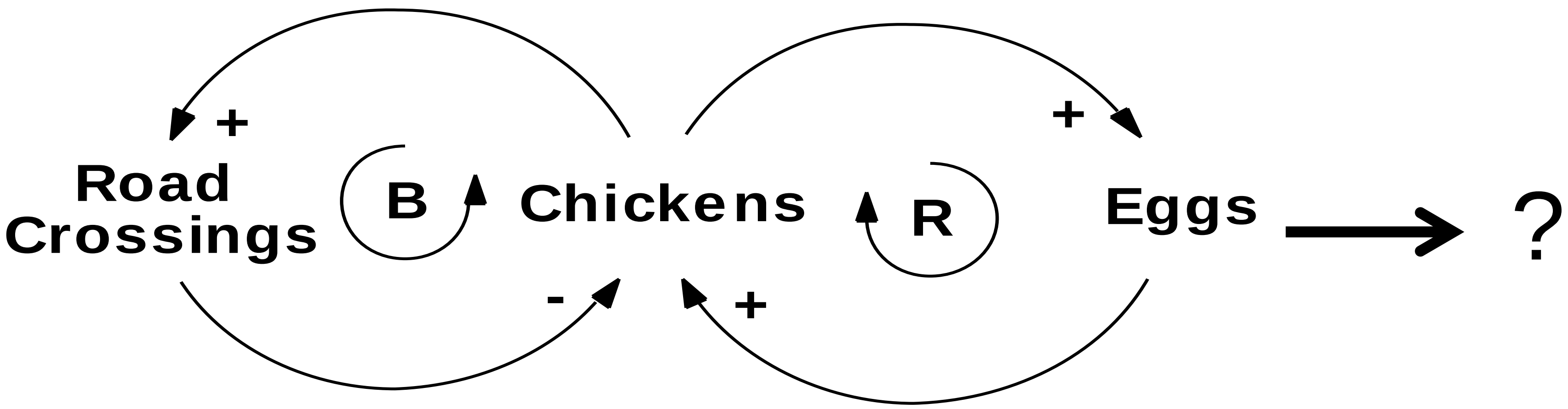
Misperceptions of Accumulation

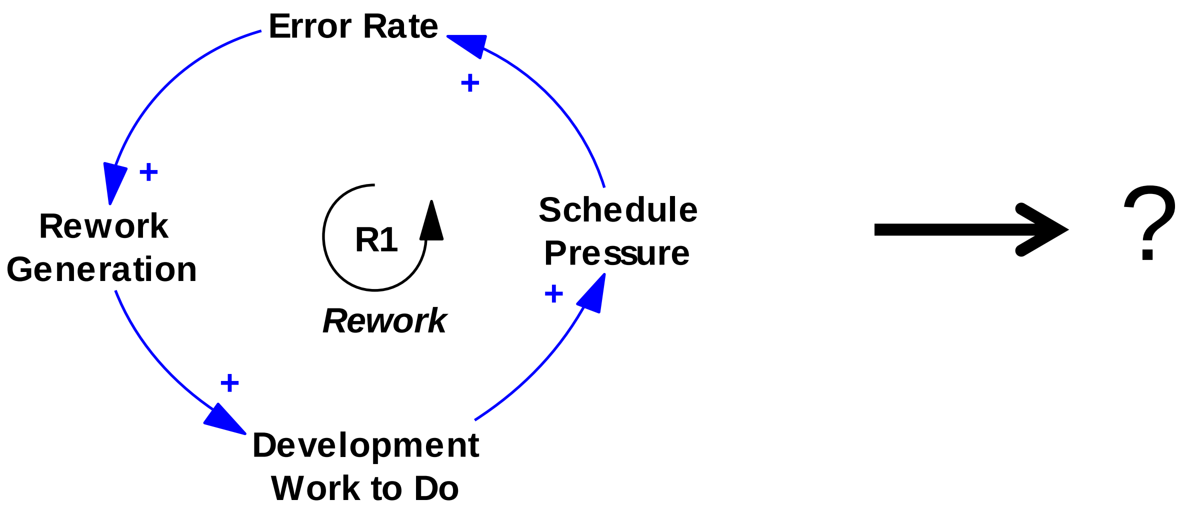
- A large literature shows that people do not have an intuitive grasp of stock and flow relationships (accumulation):
  - Pattern matching and correlation heuristic dominate (e.g. if deficit is going down, people expect debt to go down as well)
  - When combined with feedback misperceptions, they create a potent recipe for poor learning and judgment and decision making biases
- Formal modeling helps with building our skill in understanding the impact of accumulation

System Structure Diagrams

- Combining CLDs with Stock and Flows
- Select the stock variables in the CLD and redraw the diagram with explicit stocks and flows identified
  - A major step towards quantifying the models
  - Some of the most critical modeling decisions made in this step (how to pick the most informative stocks that capture the dynamics of interest with minimum complexity)
- Useful diagram for communication purposes
- All loops should have at least one stock in them (in a complete model)
  - Instantaneous circular causality is impossible

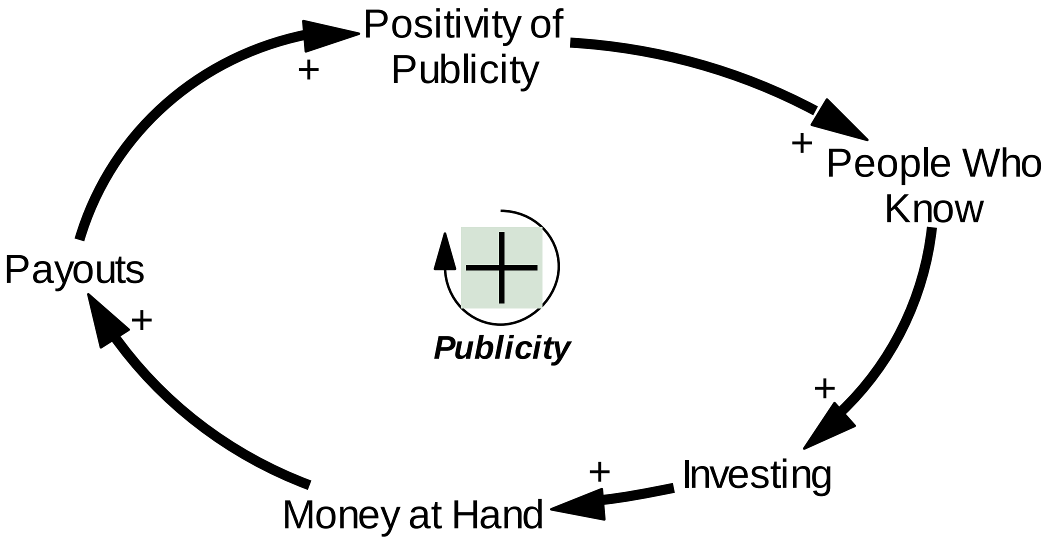
Connecting Feedback to Stocks, Flows





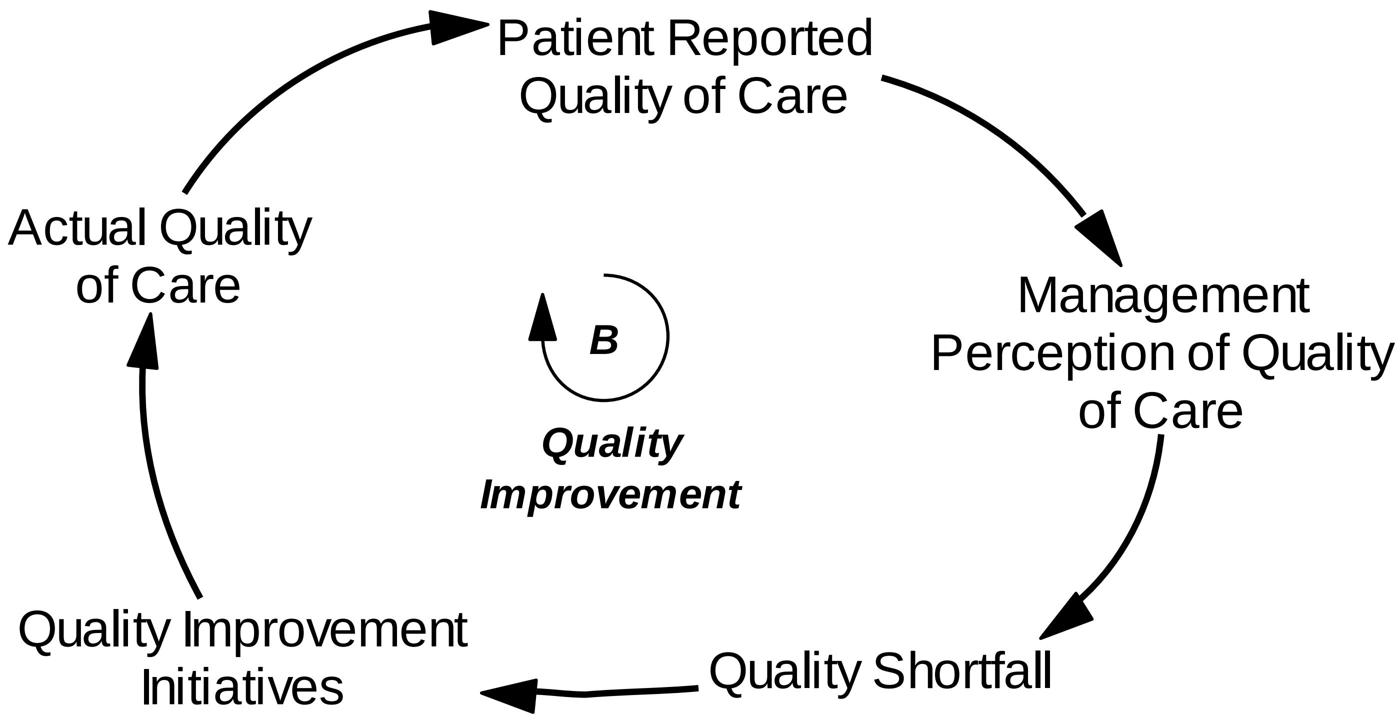
Hands On: Madoff Publicity

- **Decide what are the stocks for this loop:**
  - **Consider the inertia in variables (or concepts around them that create the inertia)**
  - **If time constant for an inertial variable is comparable to time frame of study, then it is a good candidate for being/suggesting a stock variable**



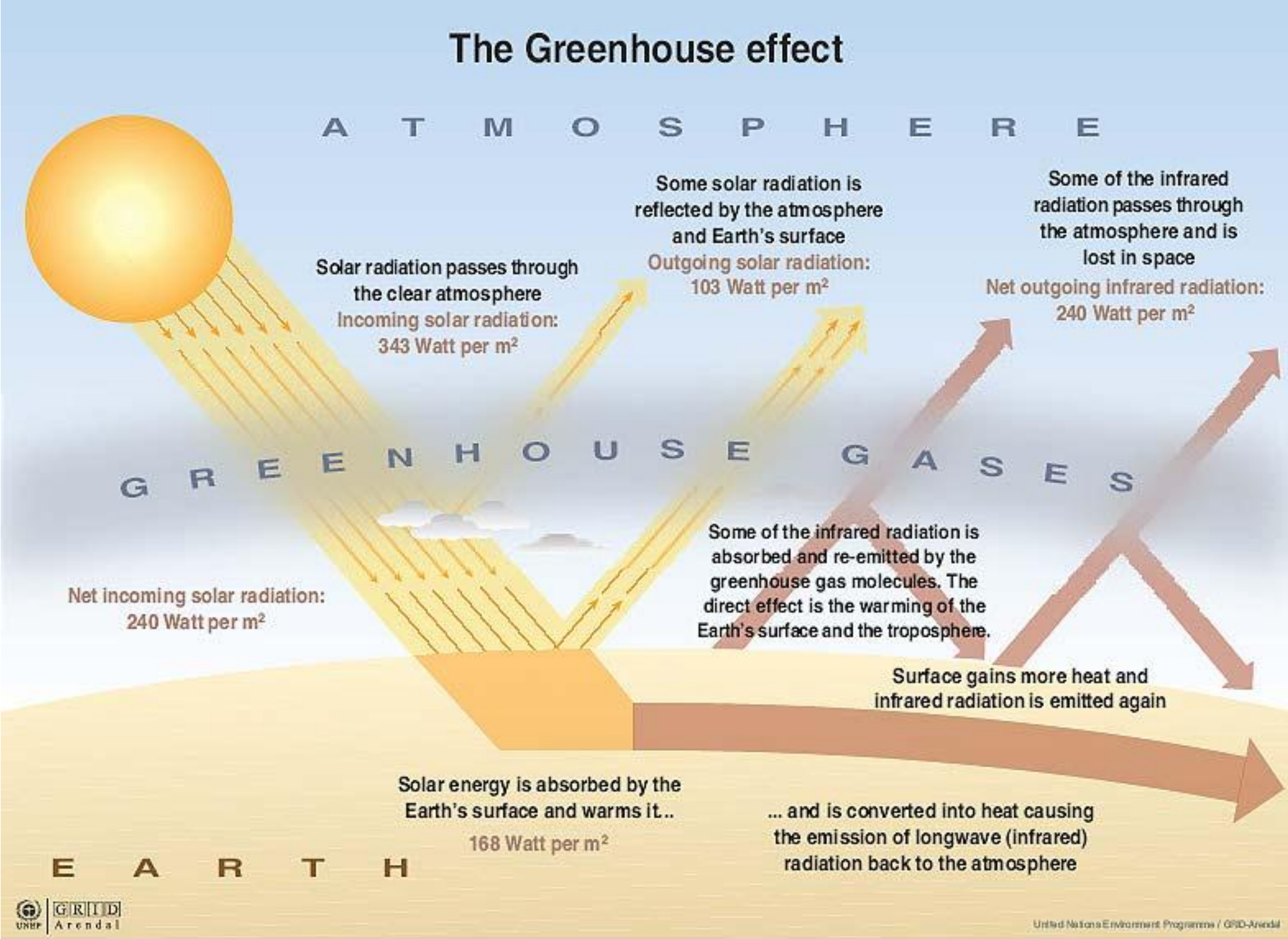
Hands On: What are the stocks

Context: Quality improvement programs in a hospital. Time frame: ~ 2-3 years



Hands On: Global Warming

- Develop a system structure diagram (Causal loops+ stocks and flows) for global warming, based on the following description



Sources: Okanagan University College, University of Oxford, EPA, IPCC.

Global warming basics

- Temperature depends on heat (and atmospheric volume). Solar radiation increases heat and outward radiation reduces it. Outward radiation is reduced by CO_2 concentration.
- The amount of CO_2 in the atmosphere is affected by natural processes and by human activity.
  - Anthropogenic CO_2 emissions (emissions resulting from human activity, including combustion of fossil fuels and changes in land use, especially deforestation), have been growing since the start of the industrial revolution
- Natural processes gradually remove CO_2 from the atmosphere (for example, as it is used by plant life and dissolves in the ocean). Currently, the net removal of atmospheric CO_2 by natural processes is about half of the anthropogenic CO_2 emissions.

Based on this information, build a basic stock and flow structure (include only two stocks) and provide links between rates and stocks as discussed above. You will add some feedback loops to this model later.

Incorporate at least two reinforcing loops into your stock and flow diagram based on the article below

Could Global Warming Become a Runaway Train?

Scientists: 'Feedback Loops' Are the Single-Biggest Threat to Civilization From Global Warming

POINT BARROW, Alaska, Feb. 18, 2006

Recently, it was another beautiful, sunny day out on the Arctic tundra.

It may sound nicer that way—but it's a big problem for the Earth.

Scientists say the warm weather adds to global warming because of "feedback loops."

In a feedback loop, the rising temperature on the Earth changes the environment in ways that then create even more heat. Scientists consider feedback loops the single-biggest threat to civilization from global warming.

Past a certain point—the tipping point, they say—there may be no stopping the changes.

Scientists working in the Arctic report that feedback loops are already under way. As the frozen sea surface of the Arctic Ocean melts back, there's less white to reflect the sun's heat back into space—and more dark, open water to absorb that heat, which then melts the floating sea ice even faster. More than a third of summer sea ice disappeared in the past 30 years.

In the ground next to the ocean, scientists say, warming has also awakened another enormous danger—billions of tons of carbon locked up for eons by what was once frozen ground. … "The longer we wait, the worse the situation gets, and the harder it's going to be to crack."

[says a scientist].. by his calculations, the only possibility for preventing a runaway greenhouse effect on Earth is to start reducing the use of fossil fuels immediately.

http://www.abcnews.go.com/WNT/story?id=1607112&page=1

Example Solution

Challenging model boundary

- Where does absorbed CO_2 go? Is there any feedback loop there?
- What other mechanisms/chemicals are relevant to atmospheric heat balance?

Acknowledgments

- Professors Osgood, Sterman, Repenning, and Richardson provided valuable material and slides which I have borrowed from in different parts of the course
- Part of the figure on title slide comes from Drs. Milstein and Homer's work on dynamics of upstream and downstream in U.S. health care system